Characteristics of AP Bias in Spin Valve Memory Elements

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***Abstract*– Spin valve memory element biased with a pair of antiparallel (AP) coupled ferromagnetic layer was analyzed and modeled via micromagnetic simulation. In an AP structure, an external field results in a torque, causing the antiparallel magnetization (AP) axis to rotate towards the direction orthogonal to the field. In addition, due to its strength difference between the two AP layers, the magnetostatic field from the free layer of the spin valve can lead to irreversible AP axis flipping. This irreversible flipping can be effectively prevented by applying an AF/F exchange pinning to one of the AP layers to overcome the differential field from the free layer.**

***Index Terms*----Spin valve MRAM, synthetic antiferromagnet.**

I. INTRODUCTION

In a submicrometer scale conventional spin valve memory element, the magnetostatic field arising from the poles at the edges of the pinned layer yields severe adversary effects in performance[1]. Specifically, the interlayer magnetostatic interaction results in unstable parallel state and asymmetric switching fields. In order to eliminate the interlayer magnetostatic fields, a synthetic antiferromagnet can be used to replace the pinned layer, as shown in Fig. 1. A synthetic antiferromagnet consists of a pair of identical ferromagnetic layers separated by a thin metallic nonmagnetic layer. In this system, a strong interlayer antiferromagnetic exchange coupling forces the magnetization of the two ferromagnetic layers to be antiparallel (AP) to each other. Due to the magnetic flux closure within the AP structure, the free layer essentially experiences no interlayer magnetostatic field in this modified spin valve structure.

Co/Ru/Co system has been suggested for the AP structure due to its large interlayer antiferromagnetic exchange coupling[2][3]. For a Ru interlayer thickness around 7 Å, the interlayer exchange coupling between the two Co layers can be as large as 1 erg/cm^2[2][4].

For the AP biased spin valve, the magnetization in the AP structure needs to be rigid, just as the magnetization of the pinned layer in the conventional spin valve. However, the strongly antiparallel interlayer exchange coupling alone will not ensure the rigidity of the magnetization in the AP structure. In this paper, theoretical analysis and micromagnetic modeling results of the AP magnetization rigidity will be presented.

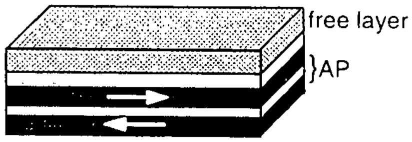

Figure 1. Schematics of an AP bias spin valve memory element.

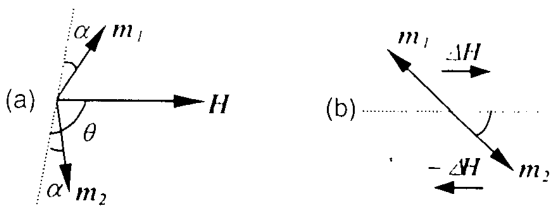

Figure 2. The field on an AP structure can be divided into (a) a common field and (b) a differential field.

II. THEORETICAL ANALYSIS

Consider an AP structure with two identical ferromagnetic layers under a uniform magnetic field, as shown in Fig.2(a). The axis along which the magnetization of the two layers are antiparallel to each other is referred to as the antiparallel (AP) axis and θ is the angle between the AP axis and the external field direction. Denoting α as the deviation angle of each layer's magnetization away from the AP axis, the surface energy area density can be written as:

$$E = -A^{*}\cos(2\alpha) - 2M_{s}H\delta\sin\theta\cdot\sin\alpha \qquad (1)$$

where A* is the surface interlayer antiferromagnetic exchange constant, M_s the saturation moment and δ the thickness of each layer. Assuming α << 1 for a strong interlayer exchange coupling, the energy density can be rewritten as:

$$E \approx -A^{*} + 2A^{*}\alpha^{2} - 2M_{s}H\delta\sin\theta\cdot\alpha \qquad (2)$$

The above equation shows that the Zeeman energy of the system can be reduced with the magnetization of each AP layer slightly deviating from the AP axis towards the field direction. The reduction of the Zeeman energy is always greater than the increase of the interlayer antiferromagnetic exchange energy as long as the deviation angle is sufficiently small. More important, this energy reduction becomes maximum when the AP axis orients orthogonal to the field.

Using equilibrium conditions to solve for α and substituting it into Eq. (1), we obtain:

$$E = -A^{*} - \frac{(M_{s}H\delta)^{2}}{2A^{*}}\sin^{2}\theta \qquad (3)$$

The reduction of the Zeeman energy over the exchange energy manifests itself as an effective uniaxial anisotropy with easy axis orthogonal to the field direction in the film plane. This is similar to the spin flop phenomenon in an antiferromagnetic material.

In the modified spin valve memory element, in additional to the external field, the AP structure also experiences the magnetostatic field arising from the edge poles of the free layer, which is always stronger for the layer adjacent to the

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free layer. Let $\vec{H}_1$ and $\vec{H}_2$ be the fields on the two AP layers, layer 1 and layer 2, respectively. They can be rewritten as:

$$\vec{H}_1 = \frac{(\vec{H}_1 + \vec{H}_2)}{2} + \frac{(\vec{H}_1 - \vec{H}_2)}{2} = \vec{H} + \Delta\vec{H}$$

and
$$\vec{H}_2 = \frac{(\vec{H}_1 + \vec{H}_2)}{2} - \frac{(\vec{H}_1 - \vec{H}_2)}{2} = \vec{H} - \Delta\vec{H}$$

where $\vec{H} = (\vec{H}_1 + \vec{H}_2)/2$ will be referred to as common field and $\Delta\vec{H} = (\vec{H}_1 - \vec{H}_2)/2$ will be referred to as differential field. Note that the analysis from Eq. (1) to (3) really applies to the common field.

The differential field generates a net torque on the AP axis(shown in Fig. 2(b)). If the two ferromagnetic layers in the AP structure are identical, the effect of the differential field is always to keep or to yield the antiparallel configuration between the magnetization of the free layer and the top AP layer.

III. MICROMAGNETIC MODELING RESULTS

A micromagnetic model using Landau-Lifshitz-Gilbert equations for multilayer structured GMR film has been developed and is utilized here for simulating the magnetization processes in AP biased spin valve memory elements.

For all the results presented here, the modeled AP biased spin valve was *Co(10 Å)/Ru(7)/Co(10)/Cu(30)/NiFeCo(30)*. The AP structure consisted of two identical Co layers with a *fcc* crystalline structure (This is always true in practice for small Co film thickness) of a cubic anisotropy $K_1=-1.0x10^5$ erg/cm^3. The Co layers were assumed to be polycrystalline with each crystallite size *100 Å* in diameter. The easy axes of the crystallites in each *Co* layer were randomly oriented. The interlayer exchange coupling between the two *Co* layers was *1000 Oe*. The free layer of the spin valve was *NiFeCo* alloy film with a saturation magnetization of *1000 emu/cm*^{3}, a thickness of *30 Å*, and an induced uniaxial anisotropy field of *5 Oe* in the direction of the spatially uniform applied field.

(A) *Square Elements*

In this case, a square shaped element of *0.5x0.5* μm^2 in dimension is modeled. Figure 3 shows the magnetization configurations of the AP biased spin valve when the external field was applied in the same direction as the magnetization of the free layer. The magnetization of the top AP layer was initialized to be parallel to that of the free layer, forming the low resistance state of the spin valve. Should the AP magnetization configuration be rigid, the parallel state would have been unchanged under the applied field. However, when the field magnitude reached *40 Oe*, the AP axis rotated to the direction orthogonal to the applied field, then immediately flipped over. The magnetization direction in the AP structure became irreversibly reversed. (Note that during this process the antiparallel configuration between the two AP layers was virtually maintained). As a result, without changing the magnetization direction of the free layer, the spin valve had changed from the parallel state to the antiparallel state by the magnetization flipping in the AP structure.

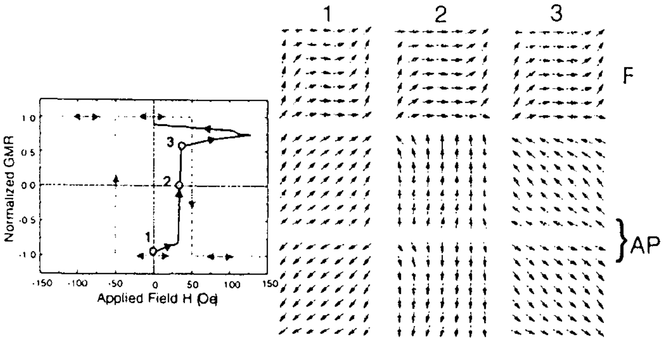

Figure 3. A calculated switching process from the parallel spin valve state (solid curve). The dashed curve represents the ideal case.

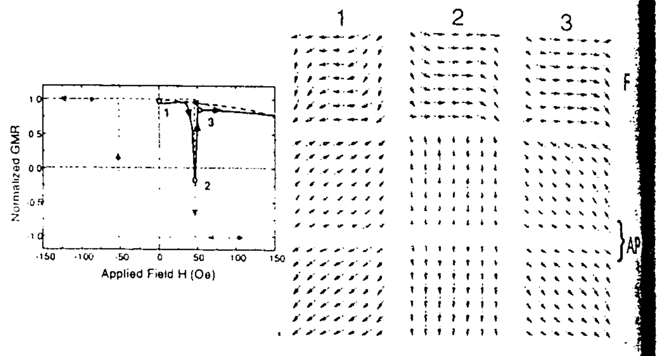

Figure 4. A calculated switching process from the antiparallel spin valve state (solid curve). The dashed curve represents the ideal case.

In the above sequence, the magnetization rotation of the AP layers was initiated by the torque corresponding to the effective orthogonal anisotropy due to the common field. The irreversible AP magnetization flipping was, then, driven by the differential field, resulting in the final antiparallel configuration between the free layer and the top AP layer.

Figure 4 shows the process for trying to switch the spin valve from the antiparallel state to the parallel state. As the free layer started its switching under the applied field, the magnetization in the AP structure also rotated. When the magnetization of the free layer reversed its direction, the AP axis was also rotated orthogonal to the field direction. The differential field on the AP then drove the magnetization of the AP layers to flip over. As a consequence, the parallel state was not reached since the magnetization of both the free layer and the AP structure had switched together, maintaining the

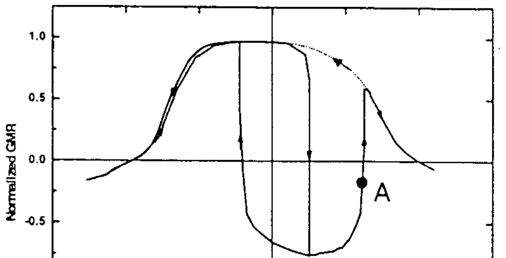

Figure 5. Calculated GMR hysteresis curve of an elongated element.

antiparallel configuration of the spin valve.

In summary, without additional anisotropy constraints, the magnetization of the AP structure can rotate and flip, even at small fields.

(B). *Elongated Elements*

In this case, the effect of element shape anisotropy for constraining the magnetization of the AP structure was investigated. Figure 5 shows a calculated GMR hysteresis curve for a $0.5x0.25\ \mu\ m^2$ element with the external field applied in the length direction. The irreversible switching field of the AP axis (Point A in Fig.5) became almost twice as that of the free layer.

The risk for relying only on the shape anisotropy is the possibility of multidomain formation in the AP layers. Figure 6(a) shows the magnetization configurations for the free and AP layers of a $0.9x0.3\ \mu\ m^2$ element after the external field had been cycled many times. In this case, a pair of perfect antiparallel coupled magnetization vortices had been formed in the AP layers. As a result, the corresponding spin valve GMR output curve, shown in Fig. 6(b), was dominated by the motion of the magnetization vortex in the top AP layer, rather than the magnetization switching of the free layer. It was found that the formed multidomain configuration can be rather stable in the AP structure.

(C) *Exchange Pinning with An Antiferromagnetic Film*

Since the irreversible magnetization flipping of the AP layers is driven by the differential field, applying an exchange pinning field to the bottom AP layer can be effective for preventing the flipping.

Figure 7 shows the calculated GMR output for an AP biased spin valve with an additional antiferromagnetic film for providing the exchange pinning field to the bottom AP layer, schematically shown as the insert. The memory element has a dimension of $0.5x0.25\ \mu\ m^2$. The GMR hysteresis, calculated with *50 Oe* for the AF/F exchange pinning field, shows a nearly ideal performance.

In this case, a *50 Oe* pinning field on the bottom AP layer is enough to offset the differential field by the magnetostatic field from the free layer. As a result, the irreversible AP axis flipping never occurred, even at large fields when the AP axis was virtually orthogonal to the field direction.

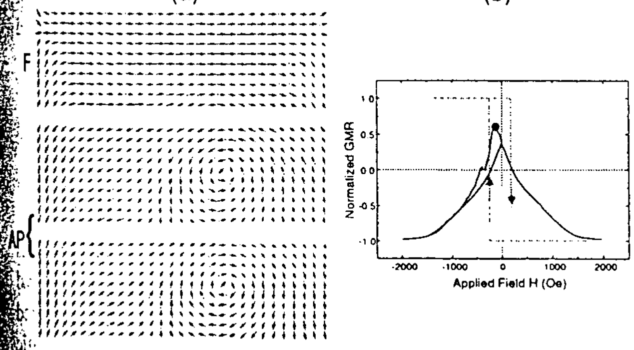

Figure 6. Calculated magnetization configurations and GMR hysteresis curve of an elongated element. The dashed curve represents an ideal case.

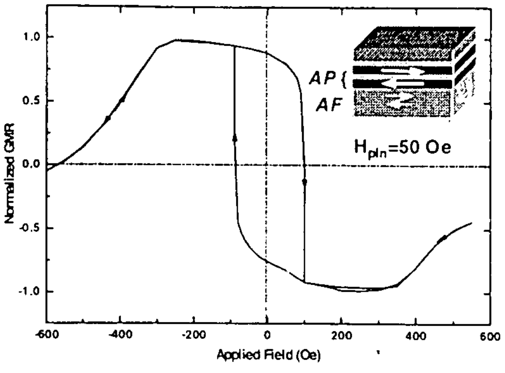

Figure 7. Calculated GMR hysteresis curve of an elongated element with *50 Oe* AF/F pinned field on the bottom AP layer.

The AF/F exchange pinning can also effectively prevent the multidomain formation in the AP structure, which can easily occur in either elongated or square elements.

IV. CONCLUSIONS

Theoretical analysis and micromagnetic modeling on the behavior of the AP bias in a spin valve memory element have been performed. An external field on an AP structure results in an effective uniaxial anisotropy with easy axis orthogonal to the field direction in the film plane. The differential of the magnetostatic field from the free layer on the two AP layers, which is always in favor of antiparallel spin valve state, can yield irreversible magnetization flip in the AP structure. To prevent AP axis rotation, an additional uniaxial anisotropy can be introduced to balance the effective anisotropy. To prevent the irreversible AP axis flipping, an additional differential field is needed to offset the differential field from the free layer.

Multidomain configurations can form in the AP layers, independent of element aspect ratio. Relying on shape anisotropy for constraining the AP axis rotation is not adequate.

Applying an AF/F exchange pinning to one of the AP layers can overcome the differential field from the free layer, effectively preventing AP magnetization from irreversible flipping. The exchange pinning can also effectively prevent the AP layers from multidomain formation.

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